Millimeter-wave Microradar Development

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The objective of this project was to enhance the low-cost impulse radar systems made famous at the Lawrence Livermore National Laboratory (LLNL) with new ranges of frequency, resolution, and directionality. Moving into these ranges opens up many new areas of application while expanding our expertise in small low-power radar systems. Several areas were identified that are leading to projects in support of LLNL programs, as well as generating new outside funding. Small, low-cost radar systems enable many applications that use arrays of transmit/receive elements, and we are pursuing many such imaging system concepts.

Introduction

In a previous report,[1] we described many of the different types of Micropower Impulse Radar (MIR) systems that have been developed in support of numerous government and commercial systems in the last few years. The main ideas behind MIR, invented by T. McEwan at LLNL, are the generation and detection systems for extremely low-power ultra-wideband pulses in the gigahertz regime using low-cost components. These ideas, coupled with new antenna systems, timing and radio-frequency (RF) circuitry, computer interfaces, and signal processing, have been the catalysts for a new generation of compact radar systems. The systems generally fall into four sensor categories: 1) motion sensors; 2) distance sensors; 3) imaging sensors; and 4) communication devices. (For more information on these systems, and on the overall MIR Project, see past reports[2] or our world-wide web page at http://www-lasers.llnl.gov/lasers/idp/mir/mir.html.)

There are still many new directions that we plan to explore, to continue our leadership role in MIR. Rather than repeat the broad list of sensors and systems within the MIR scope, in this report we will describe our efforts in FY-96 to develop higher performance (yet still small and low-cost) radars that will expand the technology base and offer more opportunities. As an entirely new technology area, rather than a single circuit, MIR has the potential to address a rich set of applications for which there is not yet program, government, or commercial support. The modular systems and higher-frequency sensors developed in the last year will inspire numerous novel concepts that have high expected impact and return on investment. We plan to embark on areas that will enhance our engineering expertise and technology base, while providing new opportunities and capabilities for programs.

Progress

The objective of this project was to expand and advance our current capabilities in MIR technology along several directions. We discuss the key technical MIR developments in terms of the technology improvements, with applications for each.

Modular MIR Components

In an effort to produce functional radar modules that can have many features to aid system development, we have designed and developed a family of MIR boards, antennas, interconnections and software with standard interfaces that "plug and play"

together. **Figure 1** is a schematic diagram of MIR modular components that fall into four general categories of software, computer interfaces, timing and baseband processing circuits, and high-speed front ends. The interconnections between the categories are based on industry standard hardware or software components (for example, SMA or audio connectors, TTL voltages, and 50-Ω terminating resistances).

The focus of our effort has been on the timing and high-speed circuitry, where much of the family has already been implemented. Incorporated into these modules are many of the anticipated enhancements needed to develop future MIR hardware systems. For this reason, the modular MIR boards are generally larger than the first generation of boards, but their layout is such that subcircuits can be easily reconfigured to build custom boards, or potentially application-specific integrated circuits (ASIC's), for particular applications. Both government and commercial projects are better served by the modular approach, because prototyping of radar systems becomes a simpler task and direct characterization of the individual components is more straight forward than with previous MIR systems.

Significant progress has been made in generating radar components that produce consistent and repeatable responses under most conditions. In contrast to earlier MIR prototypes, the current surface-mount board designs are very robust to shock, interference, and temperature changes. For example, a constant-fraction discriminator (CFD) has been added to the Dipstick and Rangefinder

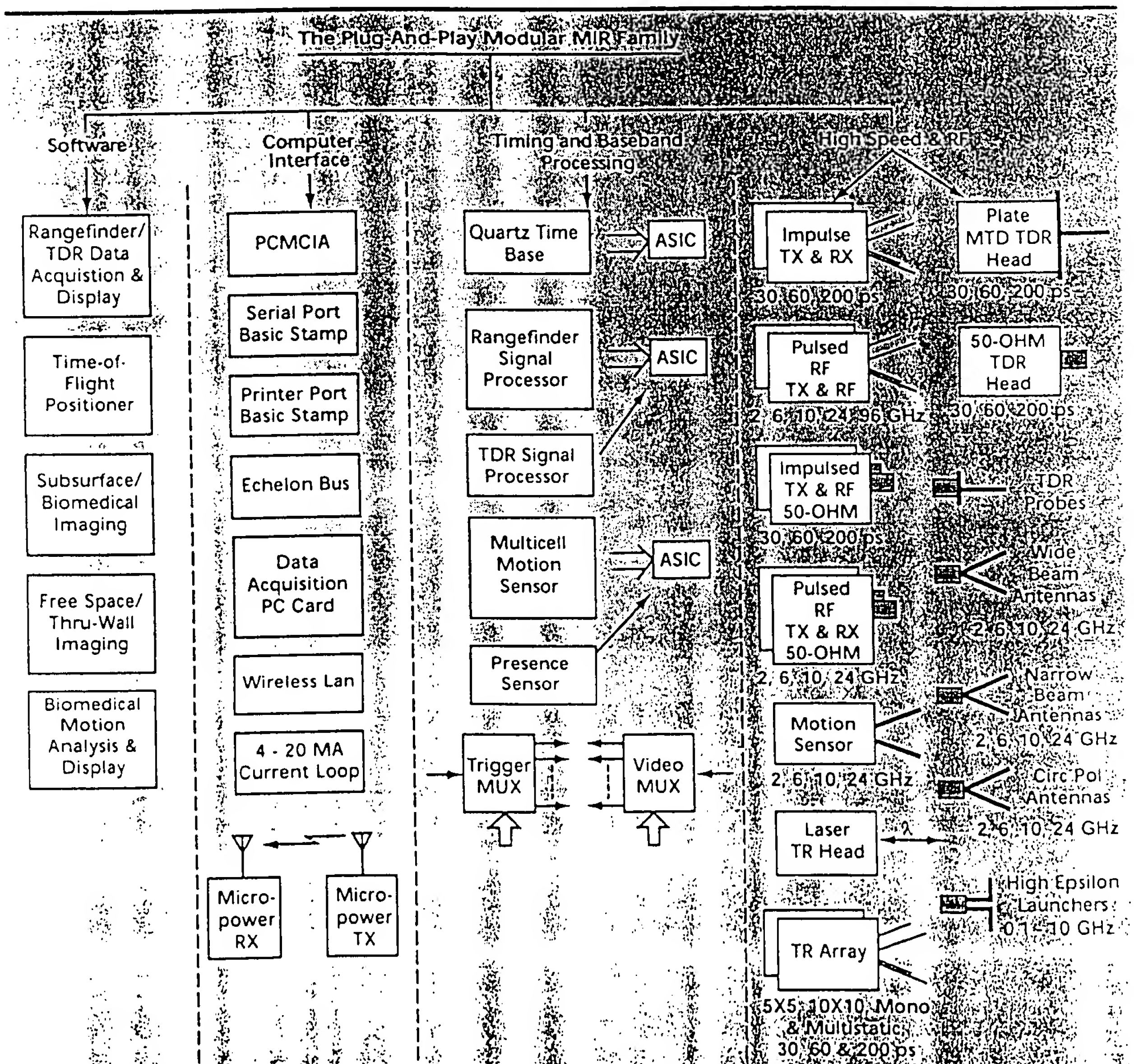


Figure 1. The MIR modular system.

systems that automatically adjusts a threshold detector to a temperature-compensated reference voltage. Then distance or range is measured by pulse-width modulation of the time between threshold crossings of MIR impulses.

For a 100-ps-wide pulse, the leading edge risetime corresponds to about 1.5 cm in range. To hold range errors below 1 mm, we need a threshold detection accuracy of better than 6%, regardless of pulse amplitude. Compensation for voltage and thermal changes (about 1% fluctuation over outdoor temperatures) is automatic and flexible enough to operate under harsh conditions.

Out of the modular components described in Fig. 1, there are several complete radar systems that have been developed in the last year.

1. MIR Motion Sensor.[3] This is an enhanced version of the single-board motion sensor that can be easily reconfigured to match a specific need. Like the original, it is range-gated, low power (multi-year battery life), low cost, channel-less (multiple MIR units can operate in close proximity without RF interference), and nearly impossible to detect. A photograph of the board with simple quarter-wave antennas is shown in **Fig. 2**.

   Only motion-modulated signals or changes from a baseline measurement are detected, thereby eliminating false triggers from stationary room "clutter." The motion pass-band can be changed by modifying the on-board filter components to match the application. An independent laboratory has verified that the MIR motion sensor can satisfy FCC Part 15 regulations. Applications are in security and energy control systems, industrial safety, robotics, vibration sensing, and speech processing.
2. MIR Electronic Dipstick.[4] This is a two-board low-cost time-domain reflectometer (TDR) system that was designed to detect the height of fluid in a reservoir or container by measuring the pulse-echo time of an MIR pulse launched along a transmission line—a simple wire. The two modular boards are the quartz time base and TDR signal processor described in Fig. 1. Measurement of the fluid height is typically resolved to 0.1% of maximum range. There are many applications of the system in measuring fluid and material levels in industrial containers (tanks, vats, silos), hazardous materials, down-hole water levels, automotive tank monitoring, and in providing automatic fill control.
3. MIR Rangefinder.[5] This is a five-board complete impulse radar transceiver system with swept range-gate and ultra-wideband antennas. A photograph of the full modular Rangefinder is shown in **Fig. 3**. The five boards used are the quartz time base, Rangefinder signal processor, 60-ps impulse receiver, and two transmitter boards (60-ps impulse and 6.5-MHz pulsed oscillator boards). The receiver works equally well with both impulse and pulsed-oscillating transmitters. Waveform outputs of the two transmitters are shown in **Fig. 4**. It generates an equivalent-time A-scan (echo amplitude vs range, similar to a WW-II radar) with a typical

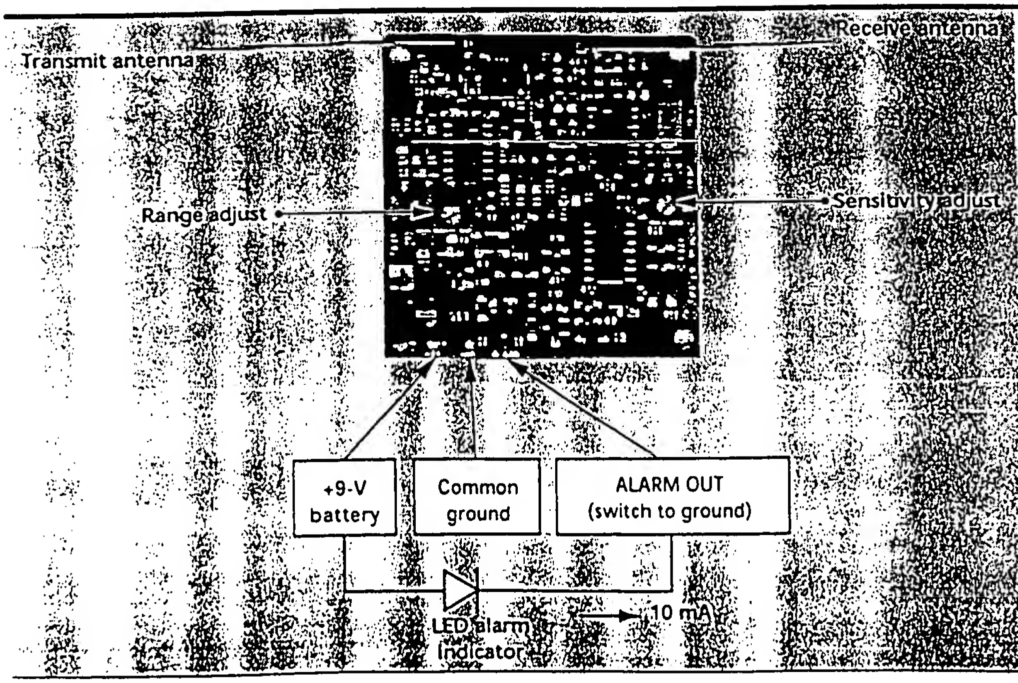
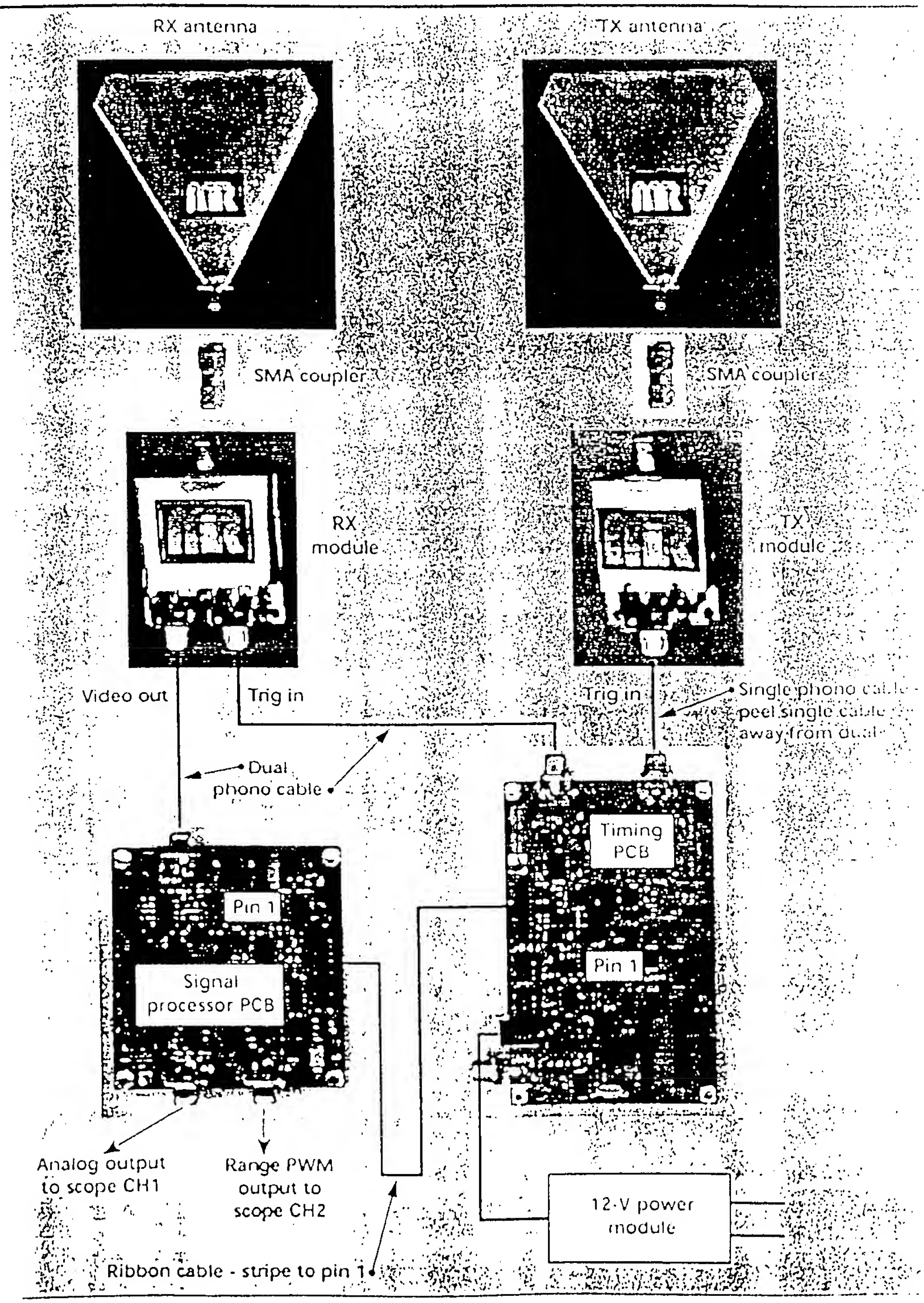


Figure 2. Photograph of the MIR Motion Sensor with simple interconnects.

...ange sweep of 10 cm to 3 m, and an incremen-... range resolution, as limited by noise, of ... mm. It operates in spectral regions that ... penetrate walls, wood panels, and to an acceptable extent, concrete and human tissue.

The MIR Rangefinder is the most sophisti-...ated of the dozens of MIR prototypes; it is the ... of all imaging applications and of many ...ursable projects. Uses of the Rangefinder include replacement of ultrasound ... ers for fluid-level sensing (a dipstick ... the stick), light-weight altimet... unmanned airborne vehicles, localiz... ing motion behind walls, vehicle heigh... ing, and robotics control. When pos... over a highway lane, it can collect ... count, vehicle profile, and approximate ... data for traffic control.

...ograph of the ... MIR ...rangefinder with ... interconnects.



Rangefinder Extensions

As mentioned in the last section, the modular MIR architecture makes it possible to extend the Rangefinder to new levels of performance and capability. Where the original Rangefinder was a fully-integrated unit with fixed antennas, the modular design adds flexibility to our prototyping efforts. During the development of the modular design, we also added improvements to the standard MIR features (without substantially adding to the cost). For example, the CFD described above is now directly integrated into the Rangefinder design. Also included are more accurate time-base generation (0.1% over the maximum range using a crystal oscillator), high- and low-frequency cut-off filter controls, and wide flexibility in the start location and length of the scan. In this section, we describe some additional extensions to the Rangefinder made possible by the plug-and-play concept.

The modular MIR Rangefinder provides the perfect vehicle for ultra-wideband imaging applications, and we are currently working on several such projects through outside sponsorship. Multiple transmit/receive modules (yet only one time base and one Rangefinder signal processor) can be configured into arrays of radars and coupled to a computer to form either synthetic aperture or real-array imaging.[6] Radar return signals are digitized and stored in the computer. Reconstruction of cross-sectional images from B-scan or waterfall type data is performed by diffraction tomography software on the computer.[7] Images of the scene are displayed directly on the screen within 10 s (in 2-D).

We have demonstrated the use of this radar package for integration into an imaging array that is small, lightweight, low power, and inexpensive, relative to existing radars. Some of the imaging applications we are exploring are road-bed and bridge-deck, inspection,[8] land mine and buried ordnance detection,[9,10] detection of underground utility lines, through-wall detection of people (for military, law enforcement, and search and rescue teams), and nondestructive evaluation (NDE) of concrete (civil structures, earthquake damage), wood (lumber evaluation, power pole rot), or, to a limited extent, living tissue (hematoma detection, kidney stones). Other materials are also possible candidates for material inspection, such as low density foams and composites.

The current arrays use monostatic imaging, but future versions will be capable of multistatic operation. The modular system makes it possible to separate the antennas to any distance and to perform both reflection and transmission experiments. In conjunction with the NDE Thrust Area, we are developing systems to explore these and other possibilities (see the article by J. Mast, in the NDE section of this report).

For the bridge-deck inspection project,[8] a high-speed radar (HSR) front-end system was developed that requires single pulse detection with no averaging so that the vehicle can travel at highway velocities and still detect subsurface flaws. While still small, the HSR has higher performance specifications (with associated higher cost and higher power) than its MIR counterpart. However, the HSR front-end hardware was made so that it attaches to the modular MIR antennas and back-end circuitry as another module to the tool set. This is another example of how all applications can now fit the common architecture.

Antennas

It will be necessary to integrate the electronics with the antennas in future versions of the imaging radar systems. This is needed to keep the

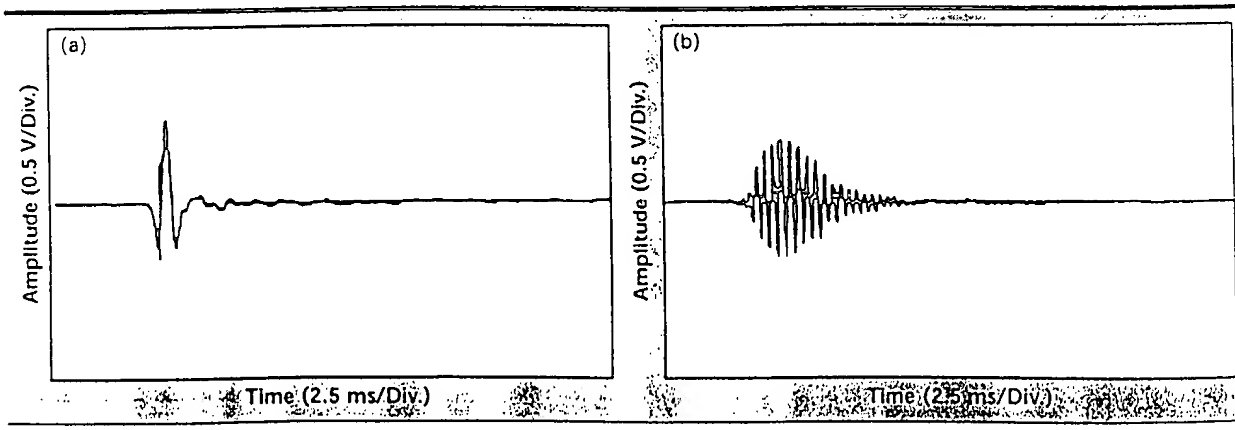


Figure 4. Video output of the MIR Rangefinder using the impulse transmitter (a) and the pulsed-oscillating transmitter (b). The transmitting and receiving antennas are pointed directly toward one another with about 20 cm stand-off.

electronics small, robust, and fast. Integrated electronics of this type will advance our capabilities in radar well beyond the current state of the art, and open numerous new areas of program development. Higher power and other directional imaging arrays may also be required for specific applications. A list of antenna constraints for the MIR Rangefinder may include:

1) s_{11} and s_{21} characteristics that are flat across a very broad band and exhibit smooth, linear phase s_{21} roll-off at the band edges;
2) group delay ($d\Phi/df$) substantially less than the impulse width across the operating band, such as less than 50 ps across 1 to 10 GHz (equivalently, very clean step function response);
3) well-controlled, low sidelobes—no change in pulse shape vs angle;
4) low feedline-coupling into the antenna; and
5) low-cost, compact, rugged, and simple construction.

In conjunction with the Computational Electronics and Electromagnetics Thrust Area, a significant amount of effort has been directed toward stable, repeatable, and scaleable ultra-wide-band antenna designs. This work has been instrumental in improving the beam-width, bandwidth, impedance, launch point, size, shape, and cross-talk characteristics of the complete MIR system. Several antenna designs are currently being used and are pending patent consideration. The basic imaging antennas have a very broad beam width and correspondingly low gain. They are suitable for synthetic aperture imaging where broad illumination is desirable. Narrower beam widths and higher gain can be obtained on a broadband basis with horns, reflectors, or dielectric lenses.

Frequency Extensions

Extending the frequency range of MIR from the maximum of about 4 GHz (microwave) into the millimeter-wave bands has been initiated in the last year. We have accomplished this with both impulse systems (wideband up to 12 GHz) and pulse-driven oscillators (at 20 GHz and 94 GHz). **Figure 5** shows the relationships of frequency range to resolution and penetration depth. By going to higher frequencies, wavelengths become shorter, antennas become smaller, and resolution improves to the millimeter range. Pulses at these higher frequencies can be launched more directionally and with lower sidebands. Penetration into materials is much less, but the resolution (on the order of 1/4 wavelength) is much greater. Also, for most applications the pulse will be launched in air, where losses are small. In all cases, we use the modular MIR timing and video processing on the back end while emphasizing research in the pulse driver circuitry.

An important advantage of moving into the millimeter-wave bands is that very high-gain antennas can be designed, which are small when compared to antennas with similar gain in the

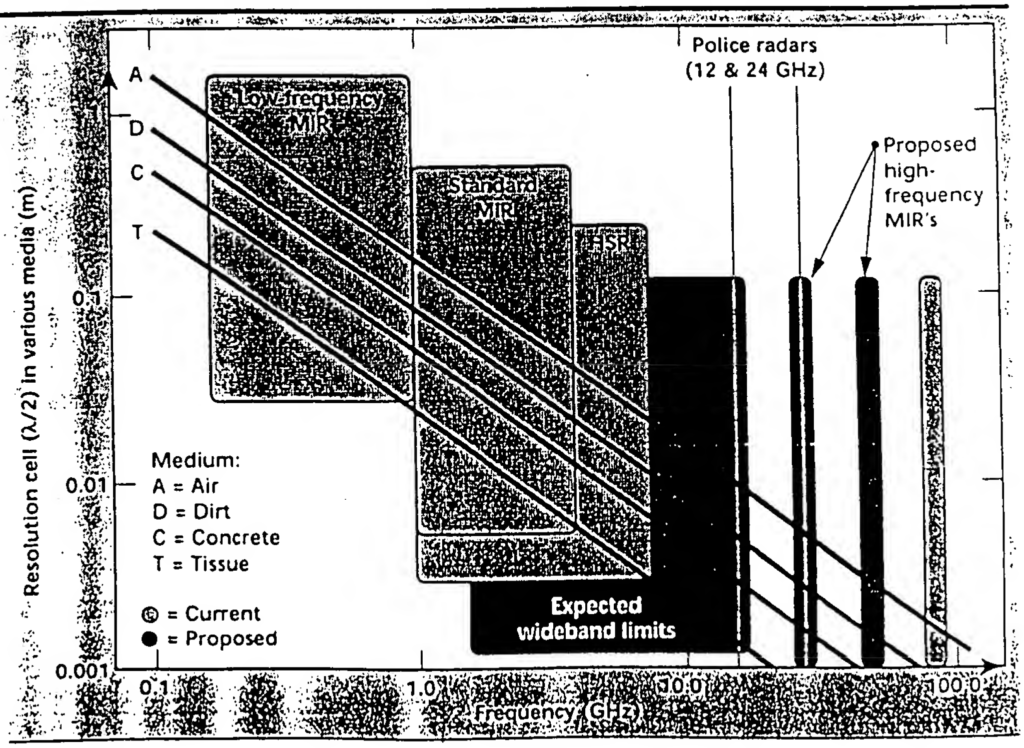


Figure 5. Frequency ranges of current and proposed MIR subsystems. Notice that the resolution improves (gets smaller) as the frequency increases, but the penetration in most materials decreases at the same time.

current MIR operating frequency band. Reasonably-sized millimeter-wave antennas, with improved gain and directivity can be produced to extend the range of MIR, and improve angular resolution and system portability. In addition, compact high-gain antennas will enhance the performance in some of the applications for which MIR sensors have already been proven. Examples of such millimeter-wave MIR applications include bullet/projectile tracking; high-resolution target acquisition for tanks and other weapon systems; robotic collision avoidance; airport ground traffic surveillance/ tracking; automotive systems; high-resolution personnel imaging; radar aids for the blind; and NDE of composite materials.

A prototype impulse driven 94-GHz radar has been assembled to gauge the operational capabilities of impulse-driven ultra-wideband millimeter-wave radars. The test system consists of a standard MIR backend timing and signal processing module that drives a high-speed IMPATT diode sampler. This diode oscillates for several cycles at 94 GHz and drives a high-frequency transmit antenna. Return signals are measured with a similar sampler on the receiver side, and again attached to the MIR signal processing module. A plot of the resulting waveform is shown in **Fig. 6**. Initial test data indicates a radar bandwidth of >5 GHz and transmit power >10 mW. Antennas used had a -3 db beam width of 10°. Tests indicate that a properly designed impulse driven 94-GHz radar should have a transmit power >25 mW and a bandwidth >15 GHz.

With additional development it may be possible to reach full waveguide bandwidth of 35 GHz (75 to 110 GHz). Radar repetition rates from kHz to >10 MHz are easily reached. Proper design of IMPATT diode matching networks for the input-driven impulse and RF output matching could allow IMPATT diodes to be used to create radars in the 1 to 40 GHz band with bandwidths on the order of 10 to 20 GHz. Further work needs to be done to better quantify the full capability of impulse-driven millimeter-wave IMPATT diodes.

Single-antenna Systems

The early MIR systems all had two antennas, one for transmit and one for receive. In this last year, we have performed work on single-antenna systems that use the same antenna for both functions. For example, a type of motion sensor we call the Field Disturbance Sensor (FDS) has been developed with 2- and 4-GHz pulsed-oscillators. The FDS is a range-gated homodyne motion sensor with similar characteristics to the MIR, yet only a single antenna is needed, and that antenna can be a standard directional one rather than omni-directional.

The Rangefinder can also be used in a single-antenna configuration by means of another recently developed "directional sampler" circuit. To receive while still transmitting, a method is needed to cancel the transmit pulse at the sampler (receiver) input. In the directional sampler, the transmit pulse is applied to the top of a resistive bridge. The transmit pulse is divided equally by the bridge resistors and applied to a differential sampler comprised of a pair of charge-holding capacitors and diodes. The output of the differential sampler is applied to an amplifier where, properly tuned, the sampled transmit pulse is differenced to zero.

Future Work

We envision many additional refinements for the MIR systems of the future. Many of those are centered around insights gained from government and commercial interactions. Most applications also require some level of effort, such as a change in range/sensitivity/directionality, or size/-power/penetration, or pulse shape, or signal processing, to reduce it to practice. As proprietors of the MIR technology, we anticipate performing much of the "proof-of-principle" development work, while attracting private industry participation for mass production.

For FY-97, we plan to continue our progress toward higher frequencies and more modular systems. In this way, we can continue our efforts to characterize MIR systems and tailor them more

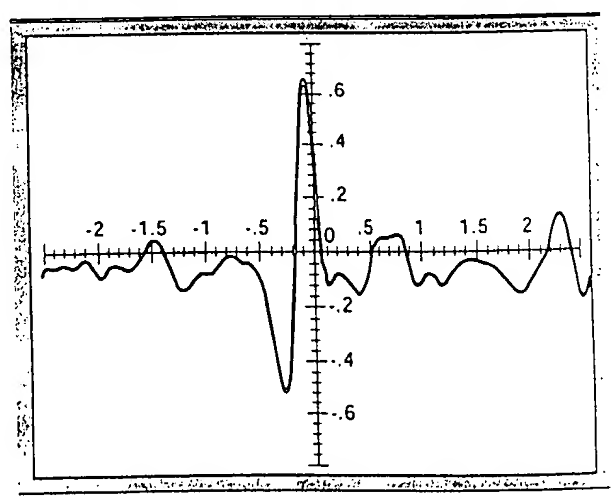


Figure 6. Pulsed 94-GHz received waveform from a metal plate at 1.32 m from the transmit/receive horns. The 94-GHz signal is sampled by the MIR back-end and shifted to the 1 to 4 GHz range.

easily to the applications at hand. There is still significant R&D needed to have reliable turn-key high-frequency MIR systems. For example, we have long considered the possibility of integrating much of the back-end MIR circuitry into a single silicon ASIC. This is still expected soon, but we will most likely carry this out in conjunction with industrial partners. While our licensees and partners are continuing to develop commercial applications of MIR, our internal efforts must stay focused on the longer-term systems issues that will take us to the next step.

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